OPERATIONAL AMPLIFIER CIRCUITS:

Design and Application

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PRENTICE-HALL, INC., Englewood Cliffs, N.J. 07632

Library of Congress Cataloging in Publication Data

JOHNSON, DAVID E.
Operational amplifier circuits.

Bibliography: p.
Includes index.
1. Operational amplifiers. I. Jayakumar, V.
II. Title.
TK7871.58.06J65 621.381'735 81-10644
ISBN 0-13-637447-6 AACR2

Editorial/production supervision and interior design: Nancy Moskowitz
Manufacturing buyer: Joyce Levatino

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

PRENTICE-HALL INTERNATIONAL, INC., *London*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*
PRENTICE-HALL OF CANADA, LTD., *Toronto*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*
PRENTICE-HALL OF SOUTHEAST ASIA PTE. LTD., *Singapore*
WHITEHALL BOOKS LIMITED, *Wellington, New Zealand*

PREFACE

The integrated-circuit revolution that began in the 1960s has remarkably transformed electrical engineering and, indeed, has wrought astonishing changes in many other aspects of our everyday lives. The fantastic shrinkage and increased reliability of integrated circuits have made possible extremely complex circuits containing many electrical elements on a single, incredibly small semiconductor chip. Integrated circuitry is responsible for a multitude of amazing devices, from the modern hand calculators to the small microprocessors and microcomputers, which perform more quickly and more reliably the tasks of computers that filled entire rooms in the 1950s.

One of the most remarkable of the integrated circuit devices is the operational amplifier, or op amp. Op amps have been around since the 1940s, but it is only as a result of integrated circuitry that they have become one of the most amazing and reliable of the analog, or linear, circuit components. The purpose of this book is to present the integrated-circuit op amp and many of its applications in electric circuits to readers who have had little or no experience with the device. The book may be used as a text for a beginning course on op-amp circuits for which the student would need only a background in elementary algebra. Even a knowledge of circuit theory is unnecessary since its essential features are given in a self-contained chapter. By ignoring the practice exercises and the end-of-chapter problems, one may also use the book as an op-amp handbook, since it contains thorough descriptions of the op amp, its terminal connections, its practical limitations, and many of its applications.

Chapter 1 is an introduction to the op amp and Chapters 3 and 4 discuss most of the basic applications using op amps, resistors, and capacitors. Chapters 5 and 6 are devoted to electric filters, which are very important and common op-amp circuits with resistors and capacitors. Chapter 7 illustrates the use of op-amp circuits in developing general analog circuits, such as those found in analog computers. Chapters 9 and 10 are a collection of op-amp applications and general guidelines that may be useful in selecting an op amp for a special purpose or for a general purpose. The applications in Chapter 9 are given in handbook fashion, and are circuits that contain diodes and transistors, as well as op amps, resistors, and capacitors.

For a reader who lacks a background in electric circuits, diodes, and transistors, or who wishes to review these subjects, Chapters 2 and 8 provide an introductory discussion. Chapter 2 deals with circuit theory in general, and Chapter 8 is concerned with diodes and transistors. These two chapters are self-contained and may be omitted without loss in continuity by a reader who is familiar with their subject matter.

To aid the reader in understanding the textual material, examples are liberally supplied and practice exercises with answers are given at the end of most sections. In addition, problems are given at the end of most chapters, with answers to the odd-numbered ones collected at the end of the book.

Four appendices are also included. Appendices A and B are data sheets for the popular μA741 and LM308 op amps, and Appendices C and D contain data needed in designing Butterworth and Chebyshev electric filters.

Many people have provided invaluable assistance and advice concerning this book. We are indebted to our students and our colleagues for the form it has taken, and to Mrs. Margaret Brewer for the expert typing of the manuscript. We also want to express our appreciation to the manufacturers who have generously supplied us with photographs of their products and information on their use.

David E. Johnson
V. Jayakumar

Baton Rouge, Louisiana

CONTENTS

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OPERATIONAL AMPLIFIERS

Electric circuits may be classified as *passive* or *active*, depending on the type of electrical elements used in their construction. Except for the input elements, which are voltage or current sources and thus are *active*, all the elements in a passive circuit are *passive* elements such as resistors, capacitors, and inductors. These elements have the advantages that they are simple two-terminal devices, no power supplies are necessary to make them work, and circuits constructed with them are always stable.

On the other hand, passive circuits cannot *amplify* signals (that is, make them stronger by making their magnitudes larger). Thus with only passive circuits we could not have radio or television or a host of other things that we accept as commonplace. Also, if the input signals have low frequencies, say 1 Hz (hertz) to 500,000 Hz (0.5 megahertz, or 0.5 MHz), inductors become impractical in electronic circuits because of their size and considerable departure from ideal behavior. Finally, inductors are not readily adaptable to integrated-circuit techniques, which are so important in today's electronic technology. Thus there is a need for *active* circuits, in which active elements are used together with resistors and capacitors to retain the effects of inductors while avoiding their actual use.

One of the most versatile, and certainly one of the most amazing, active elements is the *operational amplifier*, or *op amp*, which is the active element that we shall use exclusively in this book. As we will see, circuits made up of op amps, resistors, and capacitors can be used to perform a multitude of functions, such as adding, subtracting, integrating, amplifying, and filtering, to name a few. These include all the functions, as well as many others, that can be performed with circuits containing resistors, capacitors, and inductors.

In this chapter we introduce the operational amplifier and give its ideal characteristics. In Chapter 2, for the benefit of the reader who needs a review of the subjects, we discuss resistors and capacitors and consider some basic electric circuit principles. These will be useful to us throughout the remainder of the book, where we consider applications of operational amplifiers in electric circuits.

We will also consider limitations and practical aspects of op amps in a later chapter. However, we will defer this discussion until the reader has had a chance to see the wonders and capabilities of these marvelous devices.

1.1 INTEGRATED-CIRCUIT OPERATIONAL AMPLIFIERS

Operational amplifiers, or op amps, may be constructed by connecting individual, or *discrete,* circuit elements, such as resistors, capacitors, and transistors, in a prescribed way. A much more popular construction, however, is the *integrated-circuit* (IC) operational amplifier, in which the entire circuit is *integrated* onto a single, extremely small *chip* of semiconductor material. The IC op amp, which we will consider in this section, is more reliable, less costly, and, of course, much smaller than the discrete op amp.

Because of the vast shrinkage in element size due to integrated-circuit technology, extremely complicated circuits may occupy much less space than was formerly required for a single component. This shrinkage is dramatically illustrated in Fig. 1.1, which compares a vacuum tube with two integrated circuits. Either of the integrated circuits could contain 15 or 20 resistors and capacitors and

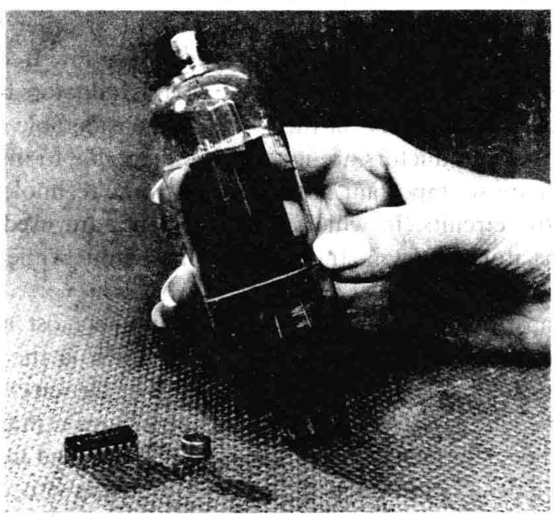


FIGURE 1.1 Vacuum-tube and integrated circuits. (Courtesy of RCA Solid State Division.)

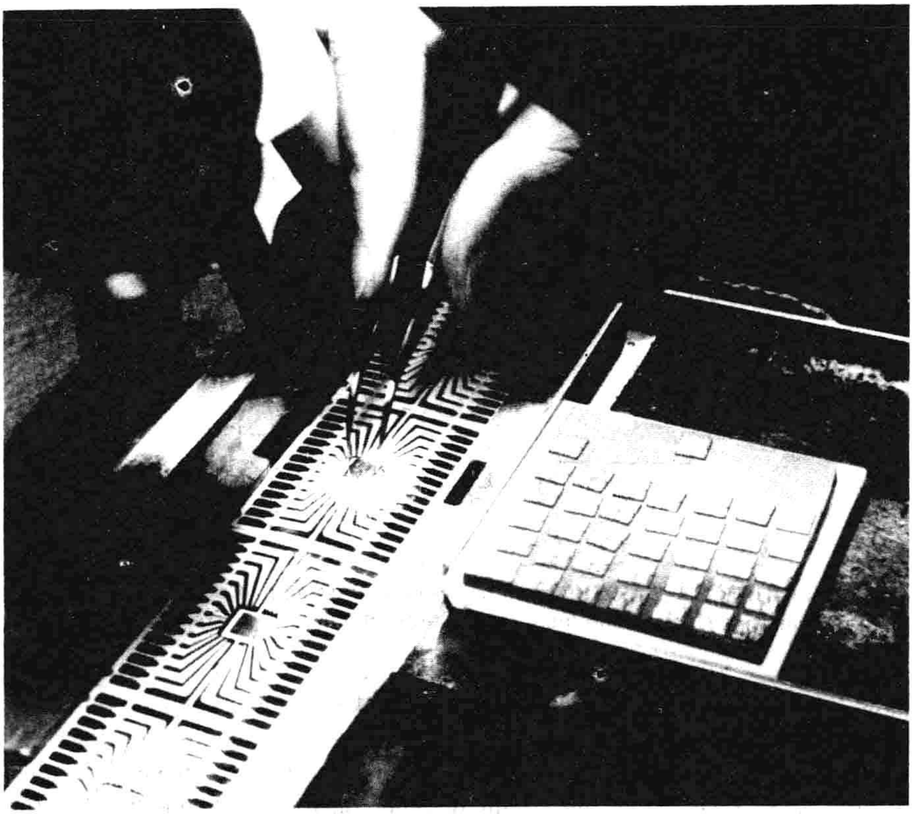


FIGURE 1.2 Integrated circuit being put in place. (Courtesy of Texas Instruments.)

as many or more transistors, each of which does the work of a single vacuum tube.

Figure 1.1, however, reveals only part of the shrinkage story. The actual circuitry is only a small fraction of the size of the integrated circuit containers. This is illustrated in Fig. 1.2, where an integrated-circuit chip is being placed in position.

The term "operational amplifier" came from the fact that the op amp, aside from being an *amplifier,* was originally a device used in circuits such as analog computers to perform mathematical *operations,* such as addition, integration, and so on. The modern op amp is still basically an excellent high-gain dc amplifier, but this is just one in a long list of its ever-growing uses. Indeed, the only limit to the op amp's field of applications seems to be the user's imagination.

Internal complexities. The op amp is a multiterminal device which internally is quite complex, as illustrated by the circuit diagram of the Fairchild μA709 op amp of Fig. 1.3. Fortunately for the user, it is not necessary to

EQUIVALENT CIRCUIT

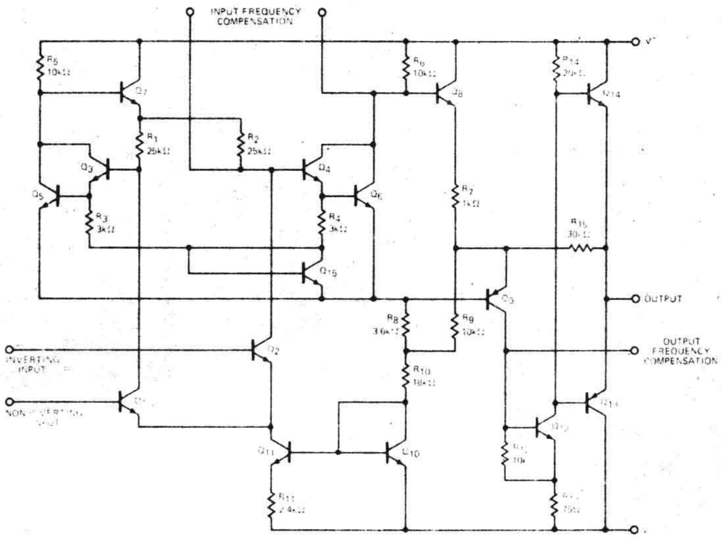


FIGURE 1.3 Circuit diagram of the μA709 op amp. (Courtesy of Fairchild Camera and Instrument Corporation.)

know anything about the op amp's internal makeup. The manufacturers have done their job so well that the op amp's performance can be completely described by its terminal characteristics and those of the external circuit elements that are connected to it. Thus the circuit designer only needs to know what the various terminals are for and how the op amp behaves externally. As we shall see, in the ideal case we only need to know the external behavior at two terminals.

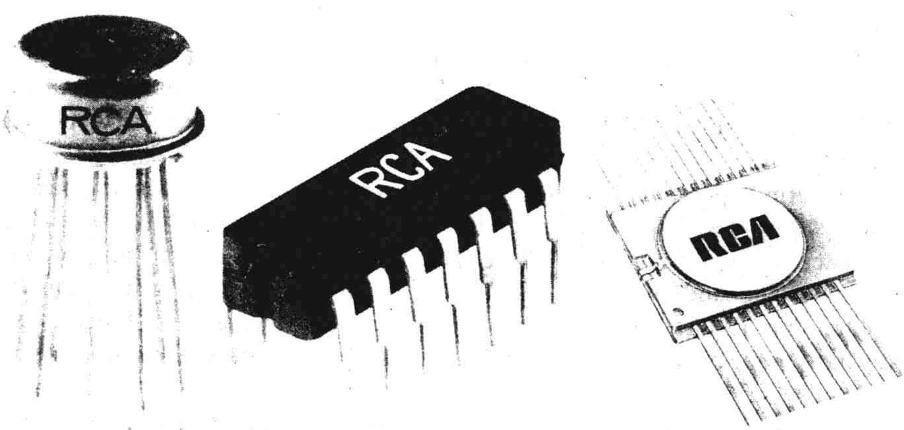


FIGURE 1.4 IC packages: (a) can, (b) dual-in-line package (DIP), and (c) flat-pack. (Courtesy of RCA Solid State Division.)

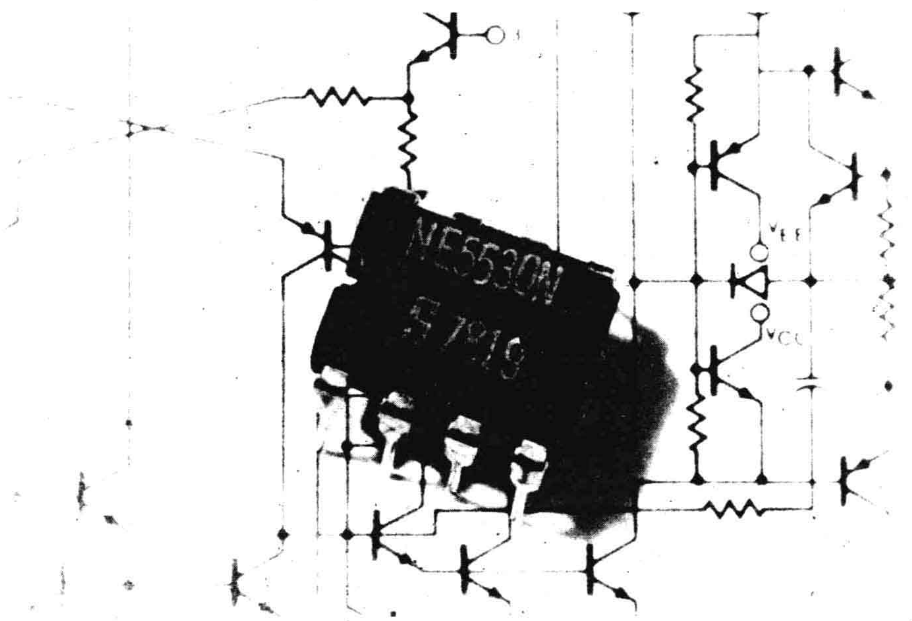


FIGURE 1.5 NE5530 op amp. (Courtesy of Signetics Corporation.)

Packages. Op amps have eight or more terminals, or *pins,* and for easy use in breadboarded circuits, come in three popular IC packages. These are the metal *can,* or *TO,* package, the *dual-in-line package* (DIP), and the *flat package,* or *flatpack,* shown in Fig. 1.4. An example of an 8-pin DIP is the NE5530 op amp of Signetics shown in Fig. 1.5.

The small size of the IC op amp is illustrated in Fig. 1.6, where two DIPs and two cans are compared in size to a dime.

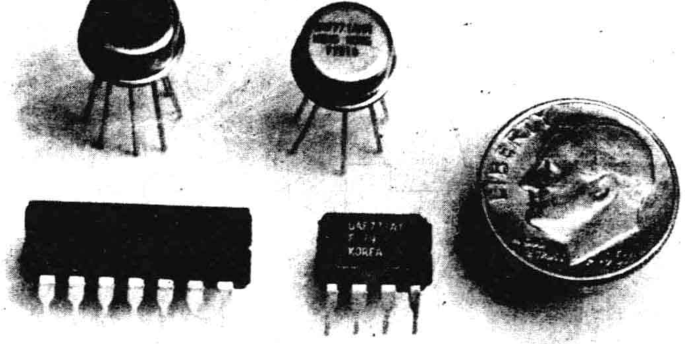


FIGURE 1.6 Op amps packaged in cans and DIPs. (Courtesy of Fairchild Camera and Instrument Corporation.)

Dual and quad op amps. Op-amp packages may contain one op amp *(single)*, two op amps *(dual)*, or four op amps *(quad)*. Typical packages have 8 terminals (the can and the DIP, or MINI DIP), 10 terminals (the flatpack and some cans), and 14 terminals (the DIP). [Note that the 24-pin flatpack of Fig. 1.4(c) is a more general IC and not an op amp, although it may contain op amps.] The μA741, for example, is a single op amp that comes in an 8-pin can, an 8-pin DIP, a 10-pin flatpack, or a 14-pin DIP. The μA747 is a dual 741 (two 741's) and comes in either a 10-pin can or a 14-pin DIP.

1.2 OP-AMP TERMINALS

Op amps have five basic terminals, as shown in the top view of a can package in Fig. 1.7. The can has eight pins, with pin 8 (or terminal 8) identified by the tab, as illustrated. The other pins are numbered counterclockwise from 8, beginning with pin 1. The basic terminals are the two *input* terminals (pins 2 and 3), the *output* terminal (pin 6), and the *power supply* terminals (pins 4 and 7), which are labeled V− and V+. The other terminals are marked NC for "no connection," but in most op amps some of these are used as *offset null* terminals or *compensation* terminals, which we will consider later. The NC pins are also used, of course, in packages of more than one op amp.

Input terminal 2 (marked − in the inner triangle) is called the *inverting* input terminal, and input terminal 3 (marked +) is called the *noninverting* input terminal. (It should be noted that some op amps, such as the Fairchild μA730, have two output terminals. We will restrict ourselves, however, to the single output type.)

Top views of connection diagrams for DIP and flatpack op-amp packages are shown in Fig. 1.8. In the case of the DIP of Fig. 1.8(a), the notch at the top locates pin 1 as the top pin on the left, and in the flatpack of Fig. 1.8(b),

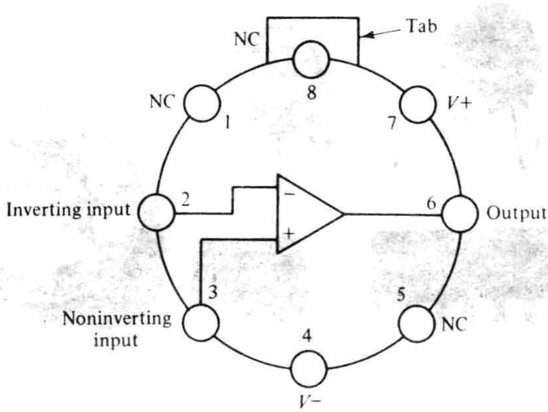
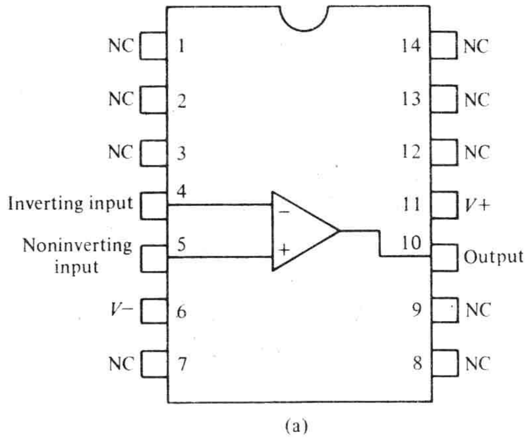


FIGURE 1.7 Connection diagram (top view) for a can package.



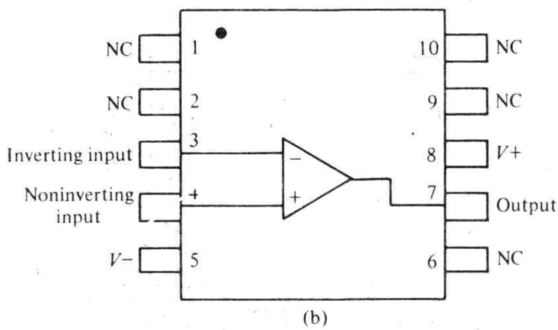


FIGURE 1.8 Connection diagrams (top view) for (a) DIP and (b) flatpack op-amp packages.

pin 1 has a dot on it for identification. The other pins are numbered counterclockwise from 1, as in the can package.

The pin numbers illustrated in Figs. 1.7 and 1.8 for the input, output, and power supply terminals are those used in many actual op amps. However, pin numbering has not been standardized and the user should consult the manufacturer's data sheet before connecting a given op amp into a circuit.

To illustrate pin numbering for packages with more than one op amp, consider the dual and quad op-amp connection diagrams of Fig. 1.9. An 8-pin dual op-amp can package, containing two op amps designated A and B, is shown in Fig. 1.9(a). The 14-pin quad op-amp DIP package of Fig. 1.9(b) contains four op amps, designated A, B, C, and D. The pin numbers are those of a Fairchild μAF772 (dual) and μAF774 (quad), and are fairly typical of dual and quad packages.

In order for the reader to become familiar with manufacturers' data sheets, we have included two sets in the appendices. Appendix A contains the data sheets for the μA741 op amp, a very popular type with offset null terminals,

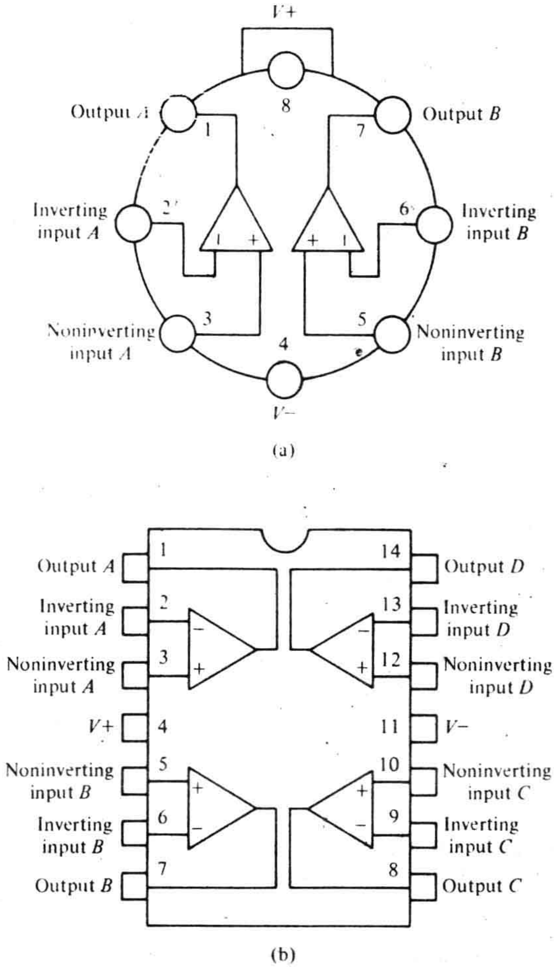


FIGURE 1.9 Connection diagrams for (a) an 8-pin can dual op amp and (b) a 14-pin DIP quad op amp.

and Appendix B contains those of the LM308 op amp, a very popular type with compensation terminals.

1.3 POWER SUPPLY CONNECTIONS

As mentioned earlier, the two power supply pins, together with the input and output pins, constitute the basic op-amp terminals. In this section we discuss the power supply connections in more detail and consider possible values of the power supply voltages.